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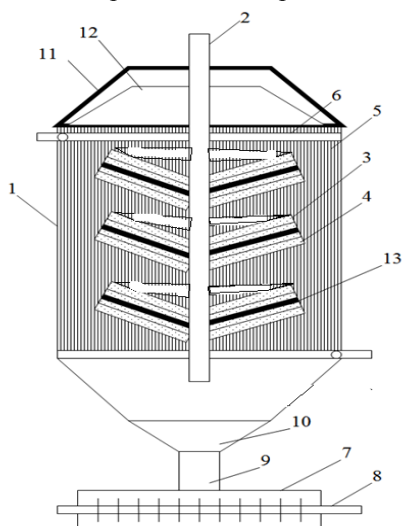
PERFORMANCE OF HEAT PUMP BASED ON COMPOSITE ADSORBENT 'SILICA GEL – CRYSTALLINE HYDRATE'

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Abstract. Performance of an adsorptive heat pump has been studied. The factors affecting the efficiency of its work have been analyzed. Operating parameters and efficiency of adsorptive heat pumps and adsorptive heat storage devices have been compared. An algorithm of calculating the basic operating characteristics of an adsorption heat pump in heat supply systems has been proposed. It involves calculating the mass transfer coefficient, final absolute humidity of the air flow passed through adsorbent layer, the water uptake or adsorption and the useful heat of adsorption and heat of condensation, determination of heat inputs for the operation of the device such as heating the adsorbent, case of the device, hydraulic circuit, the water in the tank and adsorbed water, heat of desorption and heat of evaporation, estimation the coefficient of energy performance. The evaluation criteria of the efficiency of adsorptive heat pumps and heat storage devices have been compared. It is shown that the operating parameters of the adsorptive heat pump and the adsorptive thermal energy storage device based on composite adsorbents 'silica gel – sodium sulfate' and 'silica gel – sodium acetate' are the same, i.e. airflow rate 0.08 - 0.1 m³/s and initial absolute humidity of airflow 0.03 – 0.04 kg/m³, which are corresponded with maximal efficiency of the device. The temperature of the humid air flow directed to the adsorbent layer is suggested to be set at 20 – 40 °C. The measures to increase the efficiency of the adsorptive heat pump are proposed. It is shown that ultrasonic air humidification allows to increase the coefficient of energy performance by almost 2 times compared to steam humidification. The obtained results can be used for developing energy-efficient heating systems of residential premises.

Key words: adsorptive heat pump, adsorptive heat energy conversion, coefficient of energy performance, composite adsorbent, adsorption.

Introduction. Shortening of primary fuels and rising energy prices along with air pollution and global warming makes it necessary to use all available energy resources. Promising devices are heat pumps, that is, heat transformers, in which working fluids transfer heat from a lower temperature level to a higher one during the implementation of the reverse thermodynamic cycle [1]. The most common compression (air and steam) heat pumps, based on the gradual compression and expansion of the working fluid, consume quite a lot of electrical energy during operation.



1 – adsorption-desorption type reactor; 2 – hydraulic circuit; 3 – fins; 4 – adsorbent; 5 – capacitor; 6 – cylindrical rings; 7 – evaporator; 8 – heater; 9 – a narrowing throat; 10 – distribution nozzle; 11 – cover; 12 – plate for condensate collection; 13 – fins

Fig. 1 – Adsorptive heat pump

More promising are adsorption heat pumps based on adsorption of vapor by solid substances (adsorbents), which, unlike absorptive heat pumps, are insensitive to gravity and do not require significant expenditure of electrical energy for operation and allow using low-potential heat energy [2, 3].

However, implementing of such units into convenient heating system requires a model which allows to estimate efficiency of adsorptive device according to all phases of operation. Generally, mathematical models of adsorptive devices are focused on only one phase of operating, i.e. adsorption. Moreover, efficiency of operating is estimated by only this phase [4, 5].

However, operating cycle of adsorptive heat conversion device involves the next stages: adsorption of work fluid with adsorbent or discharge and heating the adsorbent to regeneration temperature and desorption or charge, then adsorbent is cooled down to the temperatures when adsorption begins. Discharge can be accompanied by evaporation of the work fluid.

The present work is devoted to estimation of the performance of adsorptive heat pump. To achieve this aim, the next tasks are set:

- to determine basic factors affecting the coefficient of energy performance;
- to reveal correlation of the coefficient of energy performance and operating mode of adsorptive heat pump;
- to state the basic requirements to performance of open-mode adsorptive heat storage units.

Experimental. The present work is devoted to operating parameters of adsorptive heat pump. Design of its laboratory prototype is given in Fig. 1. This device contains a cylindrical adsorption-desorption type reactor 1, in the center of which is located a hydraulic circuit 2 with fins 3, which are equipped with additional jumpers, in which the sorbent 4, condenser 5, cylindrical rings 6 and evaporator 7 in the form of a cylindrical tank are placed heater 8, connected to the reactor by a narrowed throat 9. A distribution nozzle is installed in the throat 10. The lid covers the reactor from above 11. A plate for collecting condensate is installed under the lid 12. Fins 3 are mounted on welded pins 13 of the hydraulic circuit 2, which are made in the form of spirals, which are welded at an angle of 45° to the horizon [6].

The operation of the adsorption heat pump is carried out in two stages. Operational mode of heat storage unit involves two alternating phases of adsorption or discharge and charge or regeneration of the adsorptive medium. As working fluid or adsorbate water is used. During adsorption, the distribution nozzle 10 is open and through it, water vapor is uniformly supplied from the evaporator 7 due to the heat coming from the heater 8, into the adsorption-desorption type reactor 1 and absorbed by the adsorbent granules 4.

Another option for supplying moisture to the adsorbent layer is the ultrasonic humidification of the air flow, which

requires somewhat lower electrical energy consumption compared to steam humidification. Absorption of water by the adsorbent layer, that is, adsorption is an exothermic process. The heat that is released is transferred from the pellet to the pellet and to the grid, and from it to the coolant in the hydraulic circuit, and is used for the needs of the consumer.

At the second stage, the distribution nozzle 10 is closed. The heat from an external heat source, for which you can use a solar collector or a resistive heating element, is transferred through a hydraulic circuit to the one-sided finned mesh and adsorbent granules. At the same time, desorption of water vapor occurs, which condenses on the inner surface of the reactor, radial-vertical ribs and cylindrical rings with the release of condensation heat, in which a cooling coolant circulates, for example, water, which, being heated, is supplied to the consumer or reheated directly in the hydraulic circuit, then used for sorbent regeneration.

The plate for collecting condensate distributes the condensed water vapor so that it does not fall on the composite material, but flows down the walls of the case into the evaporator. Condensate flows down the radial-vertical ribs and wall of the adsorber into the evaporator through the narrowed throat.

The efficiency of adsorption heat pumps is evaluated by the thermal energy conversion coefficient COP, which is equal to the ratio of the heat supplied to the consumer with a higher temperature to the heat consumed at the same time. COP can be calculated by two methods [6]:

1) as the ratio of the useful heat, which is equal to the sum of the heat of adsorption and the heat of condensation of the adsorbate, to the sum of the desorption heat and the external heat supplied to the adsorbent during its heating to the regeneration temperature (COP_h^c);

2) as the ratio of useful heat to the heat supplied by the solar collector (COP_h^n) (op-

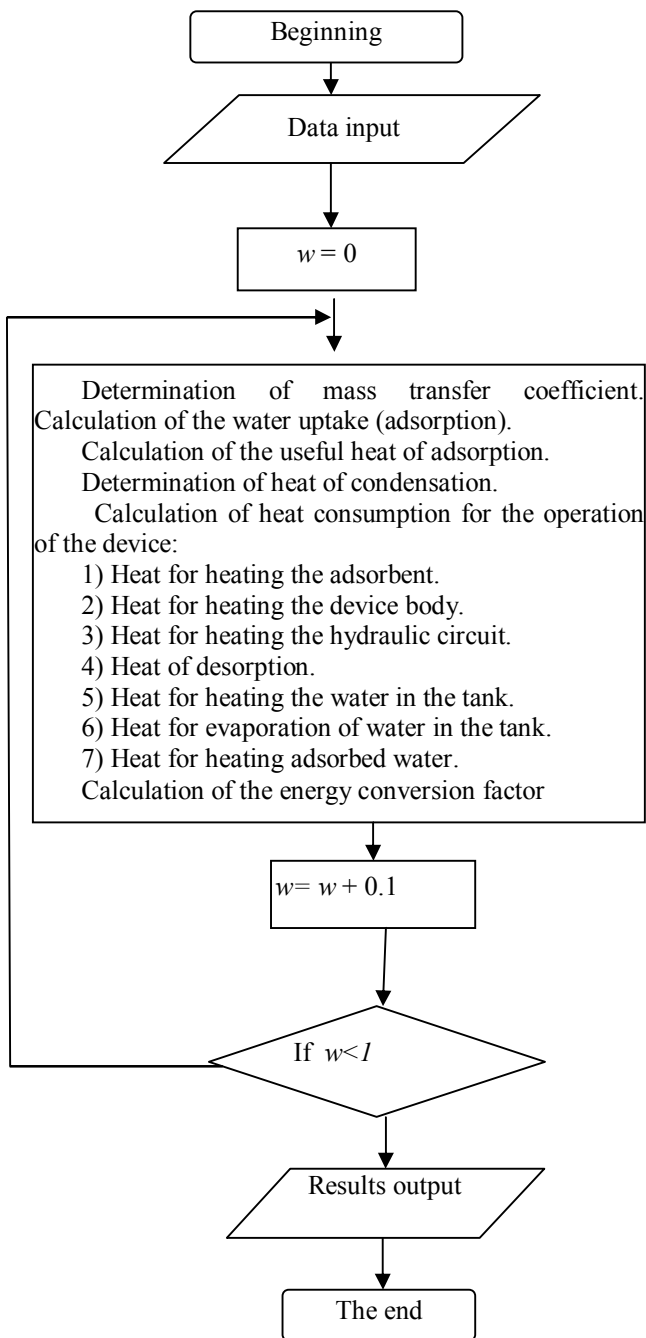


Fig. 2 – Control-flow chart of the adsorption heat pump calculation algorithm

erational).

Taking into account the stages of operation of the adsorption heat pump, a calculation algorithm for evaluating the efficiency of the adsorption heat pump is proposed. The stages of its operation are similar to a heat accumulator [6, 7]. The key differences are:

- 1) in the continuous operation of the adsorption heat pump, while a pause between the stages of discharge and charge is possible for the heat accumulator;
- 2) using the heat of condensation of the adsorbate.

In this regard, an algorithm for calculating the main operating characteristics of an adsorption heat pump is proposed, which is shown in Fig. 2.

The procedure for calculating the operating characteristics of an adsorption heat pump is similar to the calculation of an adsorption heat storage device [6]. As a criteria of energy efficiency coefficient of energy performance for heating is used:

$$COP_h = \frac{Q_{cor}}{Q_{suppl}} \quad (1)$$

where Q_{cor} is a useful heat which given to consumers, kJ, Q_{suppl} is heat inputs for operating the adsorptive device, kJ.

The useful heat is calculated as the sum of the heat of adsorption and the heat of condensation of the adsorbate, that is, water:

$$Q_{cor} = M_{ads} \cdot \Delta H_{ads} + M_{H_2O} \cdot \Delta H_{cond} \quad (2)$$

where M_{ads} is the adsorbent mass, kg, ΔH_{ads} is considered as heat of adsorption, kJ/kg, M_{H_2O} is mass of water, kg, ΔH_{cond} is heat of condensation, kJ/kg.

Heat of adsorption is calculated as [6]

$$\Delta H_{ads} = \Delta h \cdot A \cdot (1000/\mu_{H_2O}) \quad (3)$$

where Δh is heat of adsorption of 1 mole of water, kJ/mole, A is adsorption or water uptake, kg/kg, μ_{H_2O} is molar mass of water, kJ/kg.

Adsorption is calculated according with [6]

$$A = (C_0 - C) \cdot V_{air} / M_{ads} \quad (4)$$

where C_0 and C are the initial and concentration of water in the air after passing through the adsorbent layer, kg/m³, V_{air} is air volume which passed through adsorbent layer, M_{ads} is adsorbent layer, kg.

When coefficient of energy performance of cycle COP_h^c determined, heat inputs for operating the device are calculated as the sum of heat for heating the adsorbent, the device case, hydraulic circuit, water in the tank and adsorbed water, evaporation of water in the tank and desorption.

Another criterion for evaluating the efficiency of an adsorption heat pump, similar to adsorption refrigeration solar installations, is the net efficiency coefficient, which is equal to:

$$COP_h^n = \frac{Q_{ads} + Q_{cond}}{Q_{col}} \quad (5)$$

where COP_h^n is the coefficient of energy performance; Q_{ads} refers to the heat of adsorption, kJ; Q_{cond} is the heat of condensation, kJ; Q_{col} is the heat supplied by the solar collector.

Results and discussion. The effect of flow rate and absolute air humidity on the coefficient of heat energy performance of an adsorption heat pump is almost identical to the efficiency factor of an adsorption heat storage device (Fig. 3). The maximum values of COP_h^c correspond to the air flow rate of 0.08 – 0.1 m³/s and the absolute air humidity of 0.03 – 0.04 kg/m³ at the entrance to the adsorbent layer [7]. When the heat of condensation is discharged to the environment, the coefficient of energy performance is almost identical to the similar values for adsorption heat accumulators (Fig. 3a) and is more than two times less compared to the value of the coefficient of energy performance when using the heat of condensation (Fig. 3b).

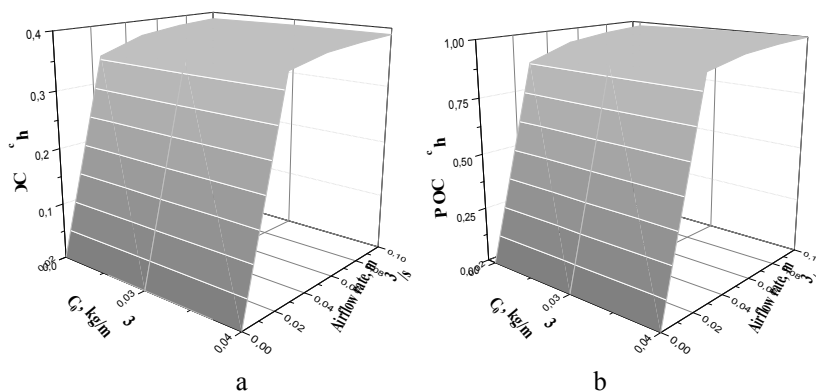


Fig. 3 – Dependence of the coefficient of energy performance for an adsorption heat pump without utilization of condensation heat (a) and with utilization of condensation heat (b) during steam humidification of the air supplied through the adsorbent layer

An increase in the temperature of the flow of moist air practically does not affect the value of the thermal energy conversion coefficient (Fig. 4), since the key factor in this case is the amount of evaporated water for air humidification, the growth of which, i.e., an increase in absolute humidity and air flow, which is supplied to the layer adsorbent, contributes to the increase of adsorption, and therefore, the heat of adsorption and the heat of condensation.

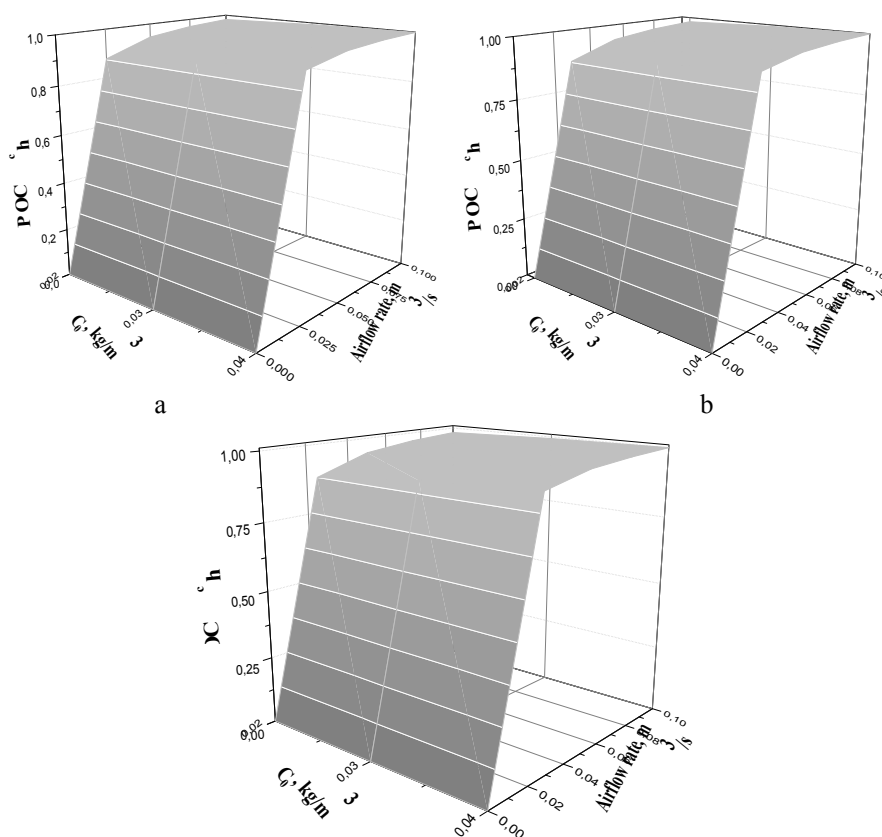


Fig. 4 – The influence of the operating parameters of the adsorption heat pump on the coefficient of heat energy conversion during steam humidification. Temperature of humid air flow, °C: 20 (a), 30 (b) and 40 (c)

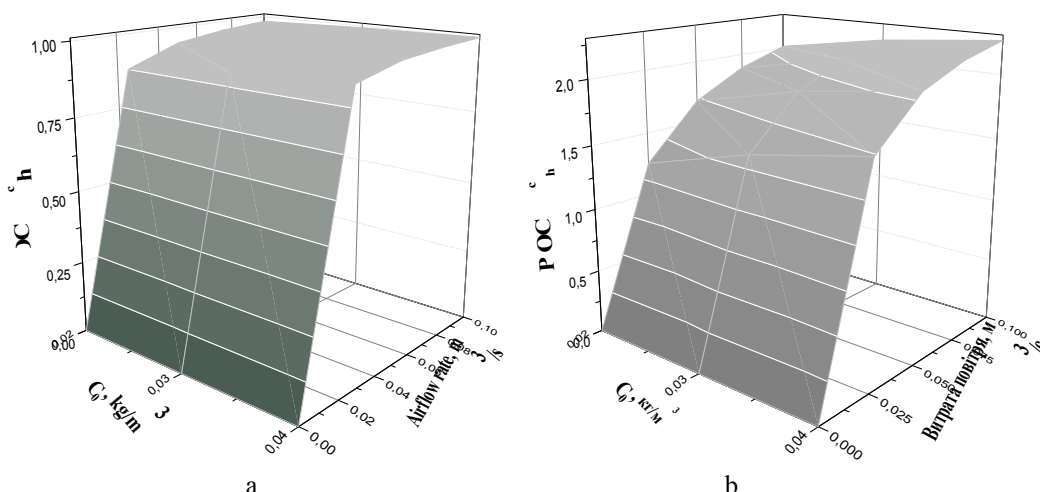


Fig. 5 – Coefficients of energy performance of adsorptive heat pump based on ‘silica gel sodium sulfate’ when steam humidification (a) and ultrasonic humidification (b) of airflow used

The calculation results are given in Table. It is noted that COP_h^c and COP_h^n of adsorption heat pumps based on both composite sorbents have practically the same value. This is due to the lower regeneration temperature of the composite ‘silica gel – sodium acetate’ (60°C) compared to ‘silica gel – sodium sulfate’ (90 °C).

Table 1

Coefficient of energy performance of adsorptive heat pump when ultrasonic humidification of air flow used

Month	Total average solar radiation flow (kW-h/m ²)	«silica gel – Na ₂ SO ₄ »		«silica gel – CH ₃ COONa»	
		COP _h ^c	COP _h ⁿ	COP _h ^c	COP _h ⁿ
May	5.99	2.084	1.130	2.021	1.189
June	5.86	2.084	1.133	2.021	1.193
July	6.06	2.084	1.128	2.021	1.187
August	5.66	2.084	1.137	2.021	1.200
September	4.41	2.084	1.176	2.021	1.257

A slight decrease in COP_h^c when using the composite 'silica gel – CH₃COONa' is a consequence of lower adsorption capacity compared to 'silica gel – Na₂SO₄'. Higher values of COP_hⁿ when composite 'silica gel – CH₃COONa' used are due to its lower regeneration temperature.

Conclusions. Operating parameters of the adsorptive heat pump are studied. The main factors affecting the efficiency of its work were analyzed. The processes of operation of adsorption heat pumps and adsorption accumulators of thermal energy are compared. An algorithm for calculating the basic operating characteristics of an adsorption heat pump in heat supply systems was proposed. The criteria for evaluating the efficiency of adsorption heat pumps and heat storage devices are compared. The parameters of the operating modes of the adsorption heat pump and the adsorption storage device are shown to be the same - air consumption 0.08 - 0.1 m³/s and absolute air humidity 0.03 – 0.04 kg/m³, which allow the operation process to be carried out most efficiently. The temperature of the flow of moist air directed to the adsorbent layer can be maintained at 20-40°C.

The effectiveness of the main measures to increase the efficiency of the adsorption heat pump is compared. The use of ultrasonic air humidification is shown to make it possible to increase the coefficient of adsorption conversion of thermal energy by almost 2 times compared to steam humidification.

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References

- Costa V.A.F., Dias, J.M.S. (2023). On the best coefficient of performance and specific heating or cooling power combination for adsorption refrigerators and heat pumps. *International Journal of Refrigeration*. doi: <https://doi.org/10.1016/j.ijrefrig.2023.04.009>
- Dias, J.M.S. Costa, V.A.F., (2022). Modelling and analysis of a complete adsorption heat pump system. *Applied Thermal Engineering*, 213, 118782
- Dai, B., Zhao, P., Liu, S., Su, M., Zhong, D., Qian, J., Hu, X., Hao, Y. (2020). Assessment of heat pump with carbon dioxide/low-global warming potential working fluid mixture for drying process: Energy and emissions saving potential. *Energy Conversion and Management*, 222, 113225. doi:10.1016/j.enconman.2020.1132
- Michel, B., Neveu, P., Mazet, N. (2014). Comparison of closed and open thermochemical processes, for long-term thermal energy storage applications. *Energy*, 72, 702 – 716. doi:10.1016/j.energy.2014.05.097.
- Gaeini, M., Zondag, H.A., Rindt, C.C.M. (2016). Effect of kinetics on the thermal performance of a sorption heat storage reactor. *Appl. Therm. Eng.*, 102, 520 – 531
- Sukhyy, K.M., Belyanovskaya E.A., Sukhyy M.P. (2020). *Technology Development for Adsorptive Heat Energy Converters: Emerging Research and Opportunities*. San Francisco: IGI-GLOBAL, USA, 328 pp. DOI: 10.4018/978-1-7998-4432-7
- Belyanovskaya, E., Lytovchenko, R., Sukhyy, K., Serhiienko, Y., Sukhyy, M., Sukha, I. (2021). Thermal conditions of adsorptive heat storage device operating in open-mode for heating inflowing air. *Scientific Works*, 85(1), 15 – 19.

ЕКСПЛУАТАЦІЯ ТЕПЛОГО НАСОСУ НА ОСНОВІ КОМПОЗИТНОГО АДСОРБЕНТУ «СИЛКАГЕЛЬ – КРИСТАЛОГІДРАТ»

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Анотація. Досліджено процеси експлуатації адсорбційного теплового насоса. Проаналізовано фактори, що впливають на ефективність його роботи. Проведено порівняння параметрів роботи та

ефективності адсорбційних теплових насосів і адсорбційних теплоаккумуляторів. Запропоновано алгоритм розрахунку основних робочих характеристик адсорбційного теплового насоса в системах теплопостачання. Він включає в себе розрахунок коефіцієнта масопередачі, кінцевої абсолютної вологості повітряного потоку, що проходить через шар адсорбенту, поглинання або адсорбції води та корисної теплоти адсорбції та теплоти конденсації, визначення теплових витрат для роботи пристрою, зокрема, нагрівання адсорбенту, корпусу приладу, гідравлічний контур, вода в резервуарі та адсорбована вода, теплота десорбції та теплота випаровування, оцінка коефіцієнта перетворення теплової енергії. Порівняно критерії оцінки ефективності адсорбційних теплових насосів і теплоаккумуляторів. Показано, що робочі параметри адсорбційного теплового насоса та адсорбційного накопичувача теплової енергії на основі композиційних адсорбентів «силікагель – натрію сульфат» та «силікагель – натрію ацетат» однакові, тобто витрата повітря 0,08 - 0,1 м³/с і початкова абсолютна вологість повітряного потоку 0,03 - 0,04 кг/м³, що відповідає максимальному коефіцієнту перетворення енергії пристрою. Температуру потоку вологого повітря, спрямованого на шар адсорбенту, рекомендується встановлювати на рівні 20 – 40°C. Запропоновано заходи щодо підвищення ефективності адсорбційного теплового насоса. Показано, що ультразвукове зволоження повітря дозволяє збільшити коефіцієнт перетворення енергії майже в 2 рази порівняно з паровим зволоженням. Отримані результати можуть бути використані для розробки енергоефективних систем опалення житлових приміщень.

Ключові слова: адсорбційний тепловий насос, адсорбційна трансформація теплової енергії, тепловий коефіцієнт, композитний адсорбент, адсорбція.

Список використаної літератури

1. Costa V.A.F. On the best coefficient of performance and specific heating or cooling power combination for adsorption refrigerators and heat pumps [Text] / V.A.F. Costa, J.M.S. Dias // International Journal of Refrigeration. – 2023. – doi: <https://doi.org/10.1016/j.ijrefrig.2023.04.009>
2. Dias, J.M.S. Modelling and analysis of a complete adsorption heat pump system [Text] / J.M.S. Dias, V.A.F. Costa // Applied Thermal Engineering. – 2022. – Vol. 213. – P. 118782
3. Dai, B. Assessment of heat pump with carbon dioxide/low-global warming potential working fluid mixture for drying process: Energy and emissions saving potential [Text] / B. Dai, P. Zhao, S. Liu, M. Su, D. Zhong, J. Qian, X. Hu, Y. Hao // Energy Conversion and Management. – 2020. – Vol. 222. – P. 113225. doi:10.1016/j.enconman.2020.1132
4. Michel, B. Comparison of closed and open thermochemical processes, for long-term thermal energy storage applications [Text] / B. Michel, P. Neveu, N. Mazet // Energy. – 2014. – Vol. 72. – P. 702 – 716. 10.1016/j.energy.2014.05.097.
5. Gaeini, M. Effect of kinetics on the thermal performance of a sorption heat storage reactor [Text] / M. Gaeini, H.A. Zondag, C.C.M. Rindt // Appl. Therm. Eng. – 2016. – Vol. 102. – P. 520 – 531
6. Sukhyy, K.M. Technology Development for Adsorptive Heat Energy Converters: Emerging Research and Opportunities [Text] / K.M. Sukhyy, E.A. Belyanovskaya, M.P. Sukhyy. – San Francisco: IGI-GLOBAL, USA, 2020. – 328 pp. DOI: 10.4018/978-1-7998-4432-7
7. Belyanovskaya, E. Thermal conditions of adsorptive heat storage device operating in open-mode for heating inflowing air [Text] / E. Belyanovskaya, R. Lytovchenko, K. Sukhyy, Y. Serhienko, M. Sukhyy, I. Sukha // Scientific Works.– 2021. – Vol 85, № 1. – P. 15 – 19.

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